# GUSTO Science

## Untangling the Complexities of the Interstellar Medium

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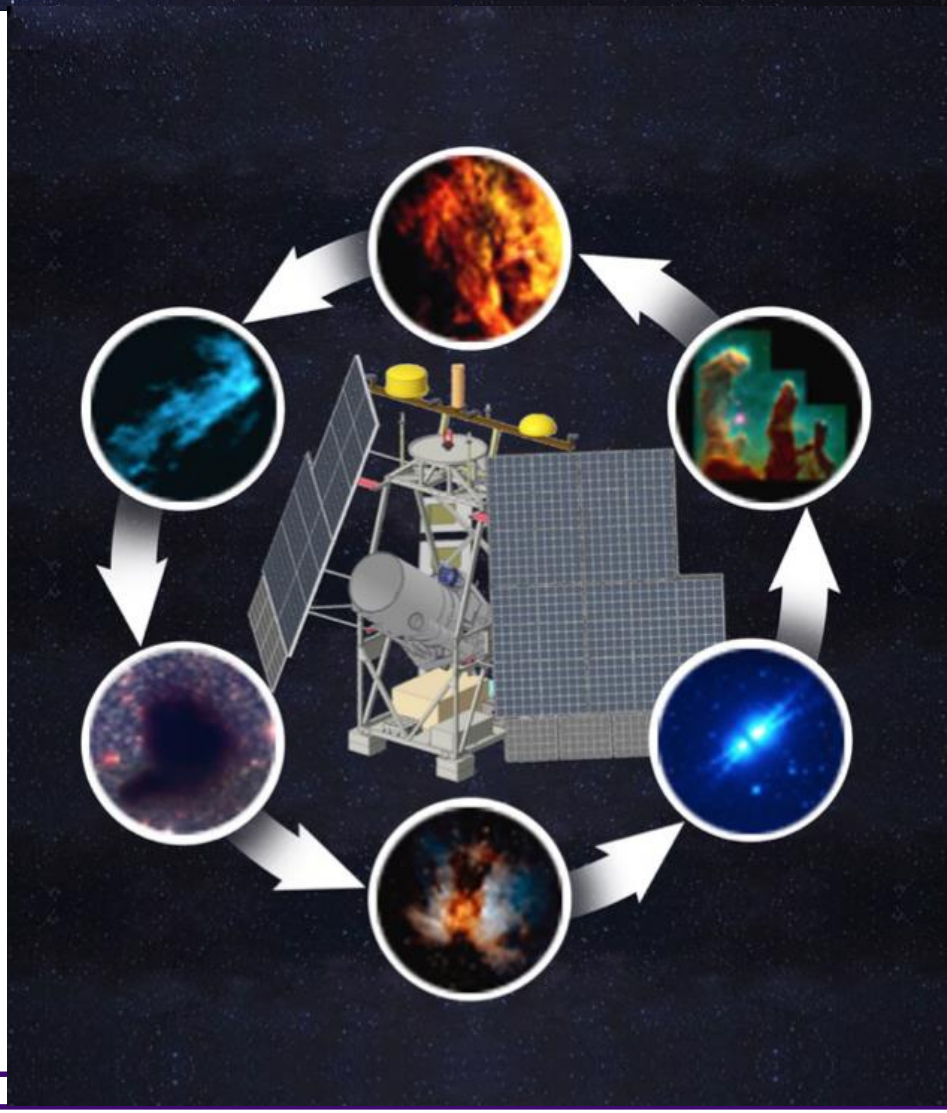


# GUSTO's Science Goals and Implementation

**Goal 1**: Determine the constituents and life cycle of interstellar gas in the Milky Way

**Goal 2**: Witness the formation and destruction of star-forming clouds

**Goal 3**: Understand the dynamics and gas flow to and in the Galactic Center

**Goal 4**: Understand the interplay between star formation, stellar winds and radiation, and the structure of the interstellar medium (ISM) in the Large Magellanic Cloud (LMC)

**Goal 5**: Construct Milky Way and LMC templates for comparison to distant galaxies

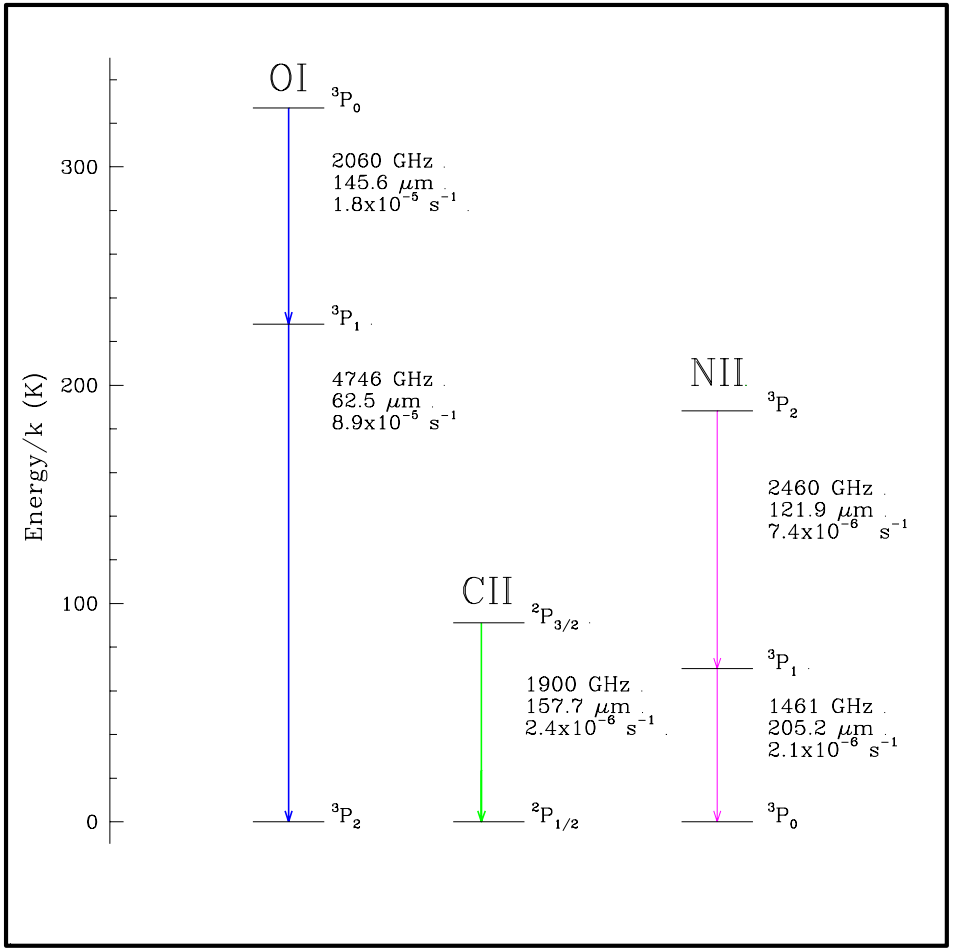
GUSTO—**the Gal/Xgal U/LDB Spectroscopic Terahertz Observatory**—will map in unprecedented detail the structure, dynamics, energy balance, and evolution of the interstellar medium within the Milky Way and Large Magellanic Cloud. GUSTO is a balloon-borne, 0.9-m on-axis telescope that will observe in three important interstellar lines: [CII], [OI], and [NII] at 158, 63, and 205 μm, respectively. With its 60" angular resolution, high-velocity resolution, and efficient "On-The-Fly" mapping strategy, GUSTO will address key unanswered questions about the stellar life cycle and provide new insights into the birth and evolution of stars and galaxies.

- ***GPS:*** *A Galactic Plane Survey (42 days)*
- ***LMCS:*** *An LMC Survey (34 days)*
- ***TDS:*** *Targeted Deep Surveys of selected regions in the Galaxy and LMC (19 days)*

# The Critical Importance of Fine Structure Line Emission

**Fine structure lines**

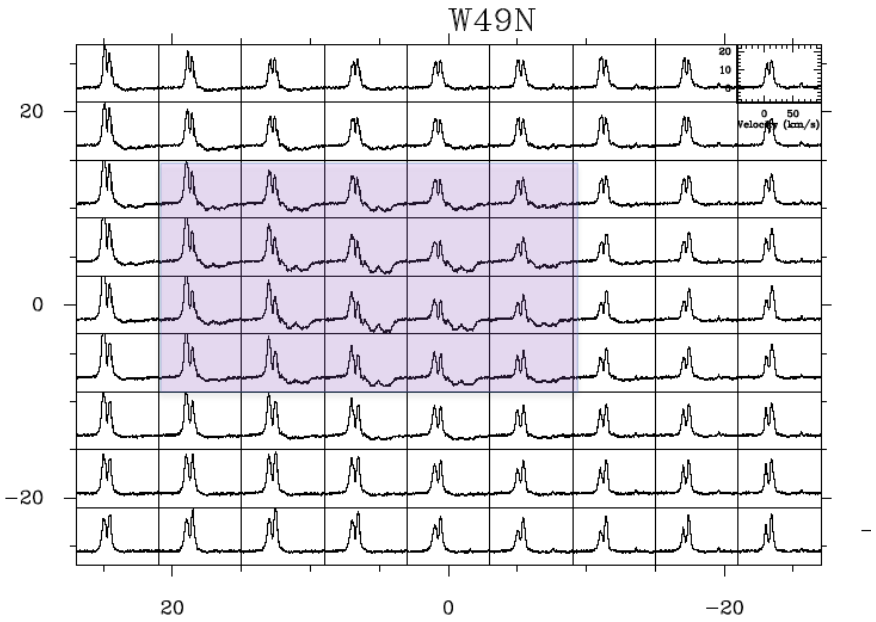
- Are the most important coolant of atomic gas in galaxies and trace the dominant component of the interstellar medium ([CII])
- Trace the energy input from massive young stars into their immediate surroundings ([OI])
- Are widely-used measures of the rate of star formation in galaxies throughout the universe ([CII])
- Trace ionized gas and help unravel [CII] emission ([NII])

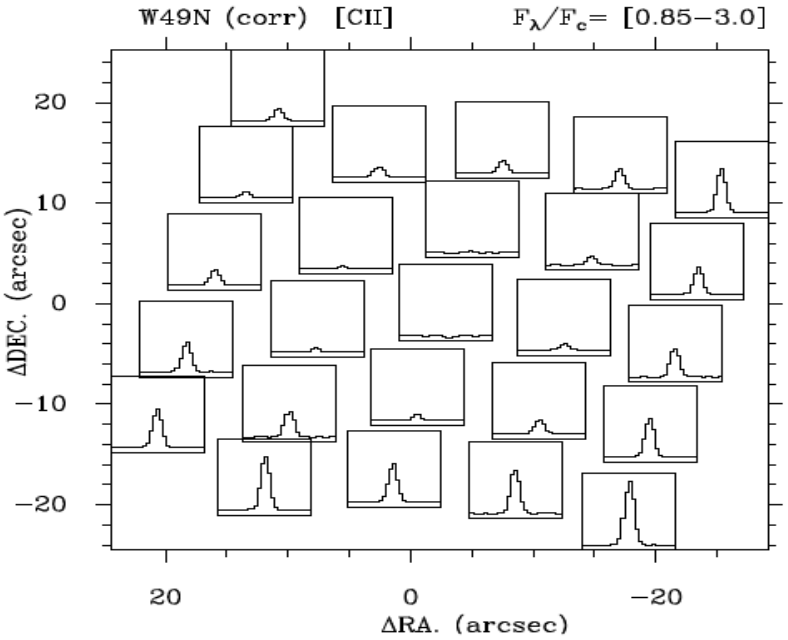



These are the three most important fine structure lines for probing structure of ISM

# Why High Spectral Resolution?

**Fine structure line emission reflects the kinematic complexity of the interstellar medium: Herschel observations**



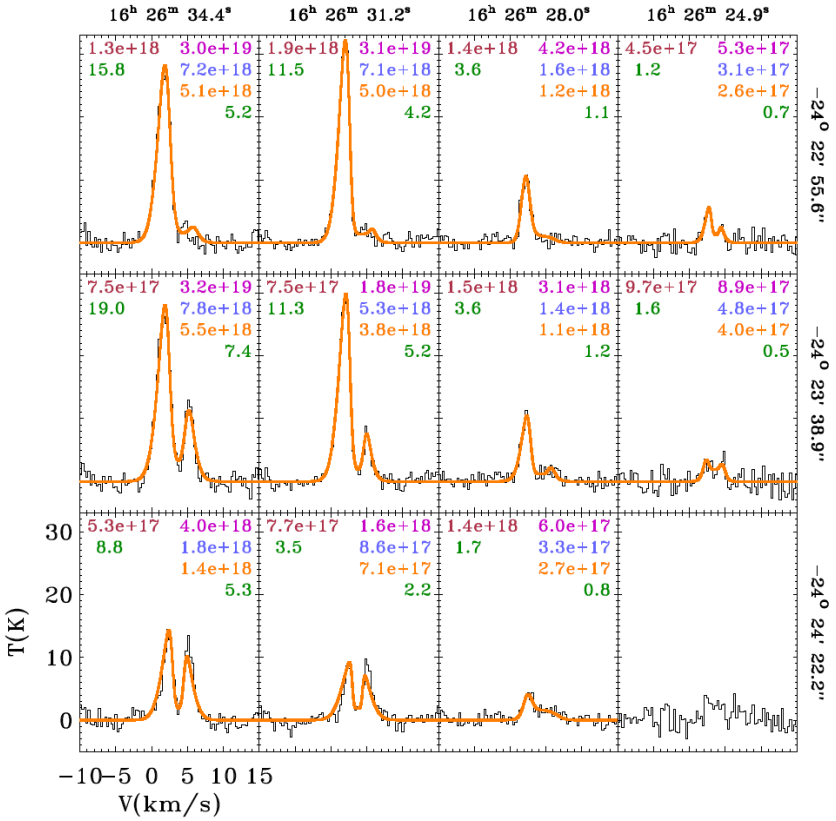

**HIGH SPECTRAL RESOLUTION: HIFI**

[CII] towards W49 (strong continuum source)
Emission is widespread; absorption shows up against the continuum
Gerin+ 2015

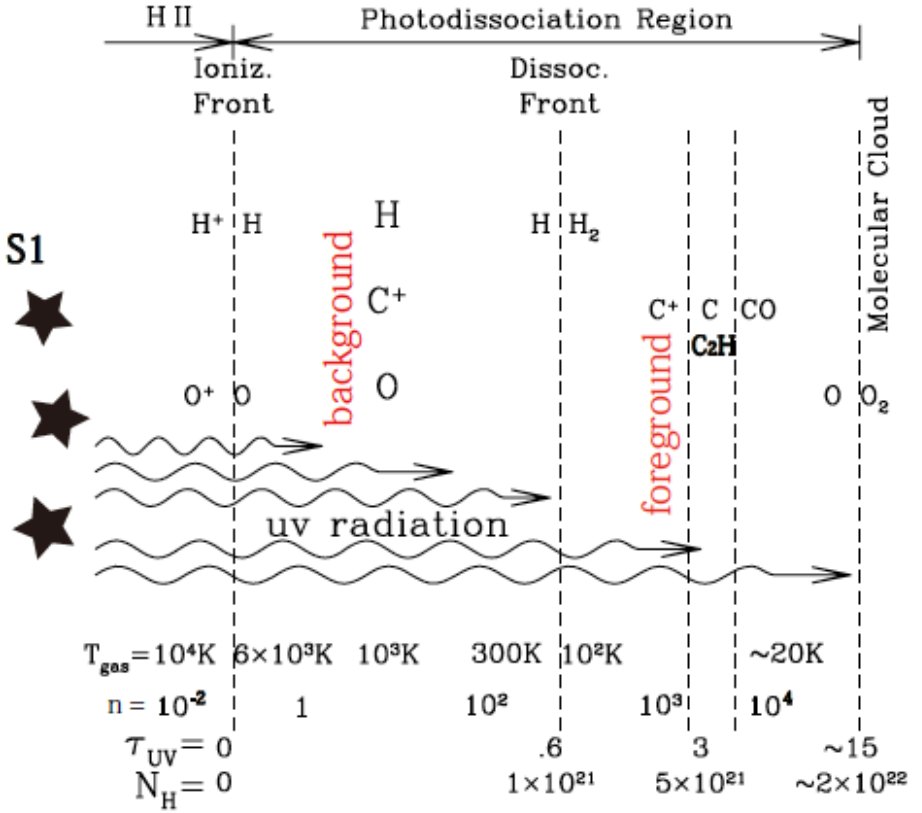
**UNRESOLVED (PACS)**

The line intensity towards the continuum source ~0; the absorption cancels the emission

# Critical Importance of High Spectral Resolution




[CII] spectra towards ρ Oph using SOFIA/upGREAT
Duo+ 2017 in preparation

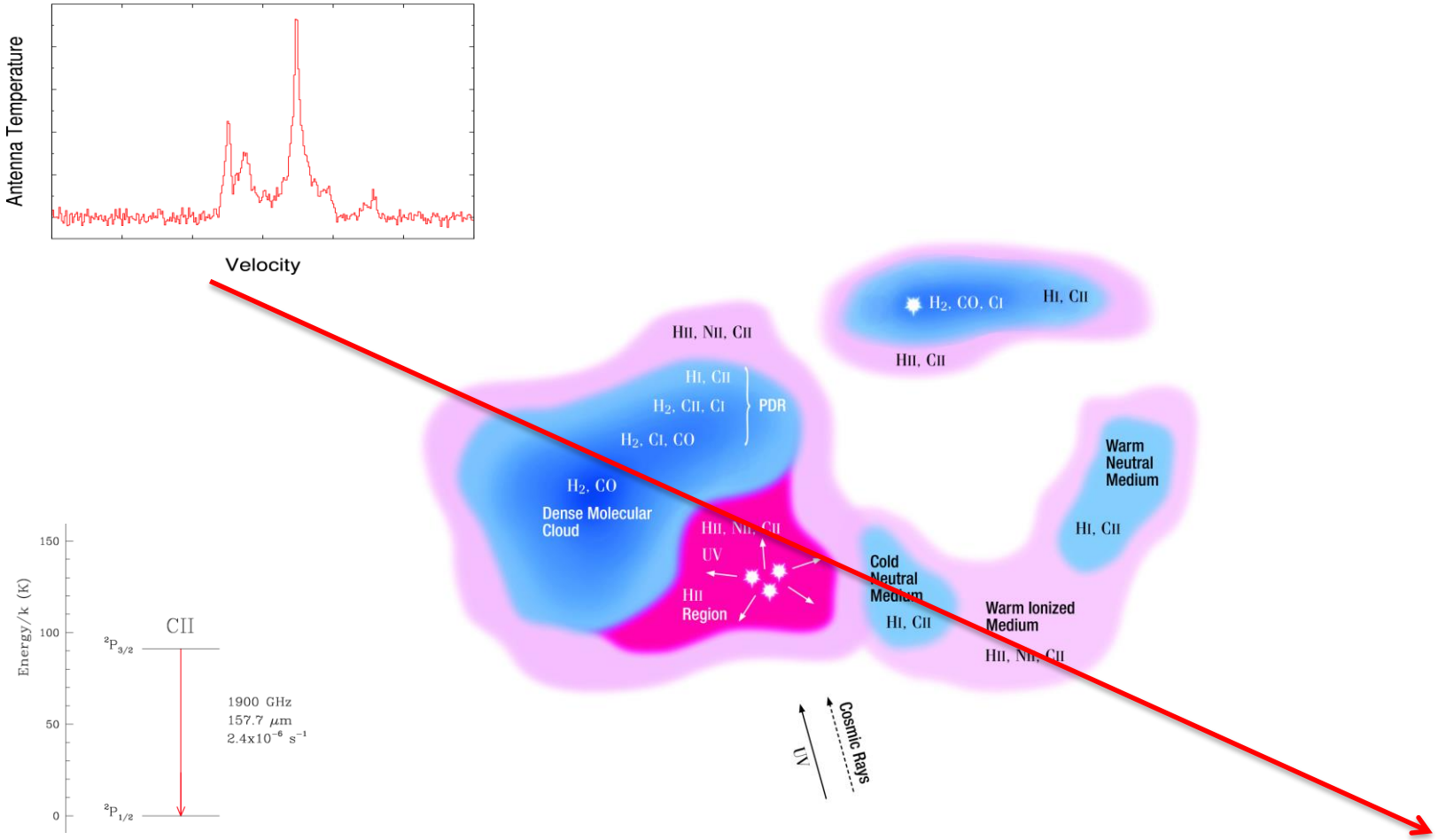



Different picture of cloud structure and energetics as well as $C^+$ column density

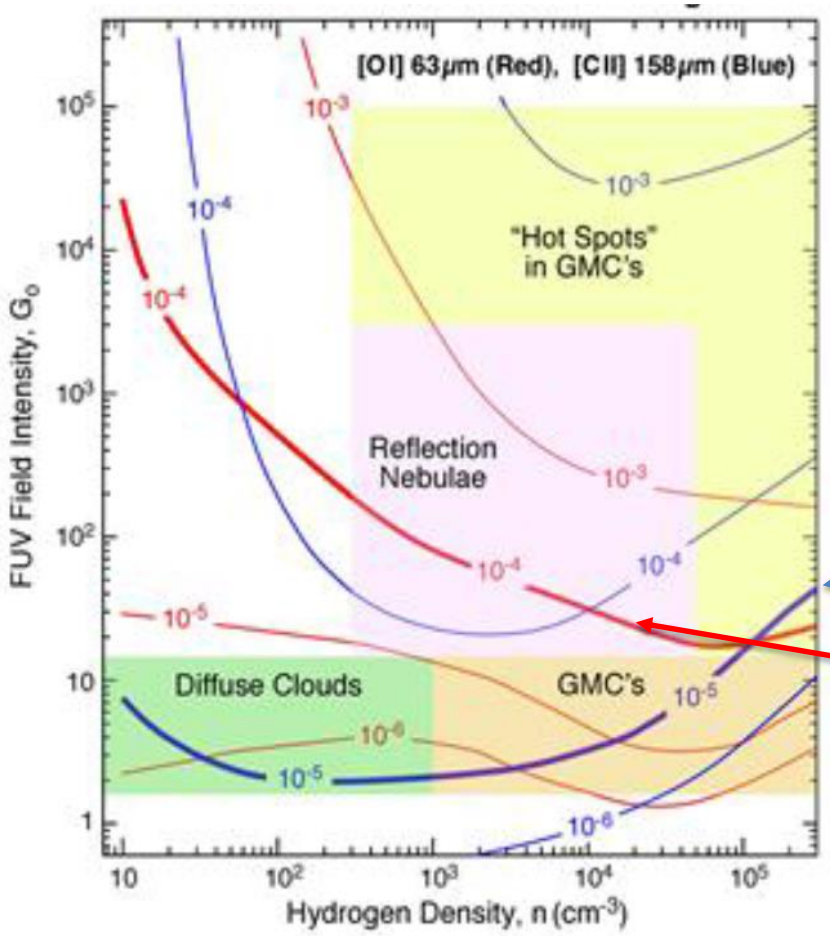


**Spectral Resolution < 1 km/s is ESSENTIAL**

# The Interstellar Medium is Complex



# GUSTO Will Transform Our Knowledge of Fine Structure Line Emission




GUSTO's sensitivity allows us to trace

- [CII] in almost all environments
- [OI] in denser, warmer regions
- [NII] in most ionized clouds (not shown)

**GUSTO 3σ Sensitivity for [CII]**

**GUSTO 3σ Sensitivity for [OI]**

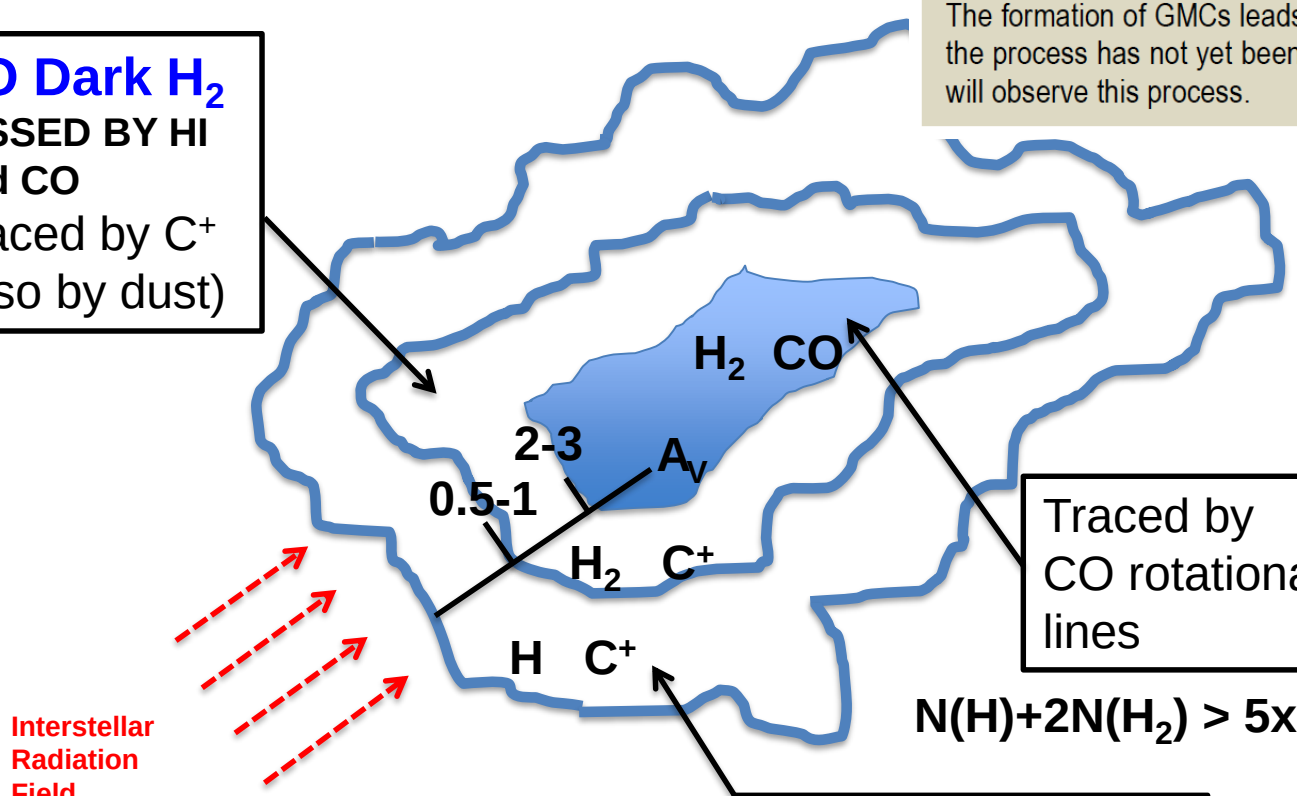
# Why GUSTO Changes the Game

- Herschel HIFI and now GREAT and upGREAT on SOFIA have given us a “glimpse” of the power of velocity-resolved spectroscopy of fine structure lines (FSLs)
- However, the limited number of pixels (1 for Herschel; 7 for upGREAT) plus limited observing time (especially for SOFIA) resulted in **ALMOST NO FULL IMAGES OF INTERSTELLAR CLOUDS**
- The few exceptions (e.g. Goicoechea+ 2015 7.5’x11.5’ map of Orion) have yielded dramatic new information about the structure of the ISM and its relationship to massive star formation
- The 100 day GUSTO baseline mission duration, 8-pixel arrays in each line observed simultaneously, and high observing efficiency will allow major imaging projects to be carried out that for the first time will allow us to see how FSL emission really works, determine the CO Dark Gas distribution, trace the energy flow in GMCs, and measure how metallicity affects the relationship between dust and gas.

# An Evolving Cloud: Enough Mass to be Gravitationally Bound

The formation of GMCs leads to most star formation, yet the process has not yet been directly observed! GUSTO will observe this process.

**CO Dark $H_2$**
**MISSED BY HI and CO**
Traced by $C^+$ (also by dust)



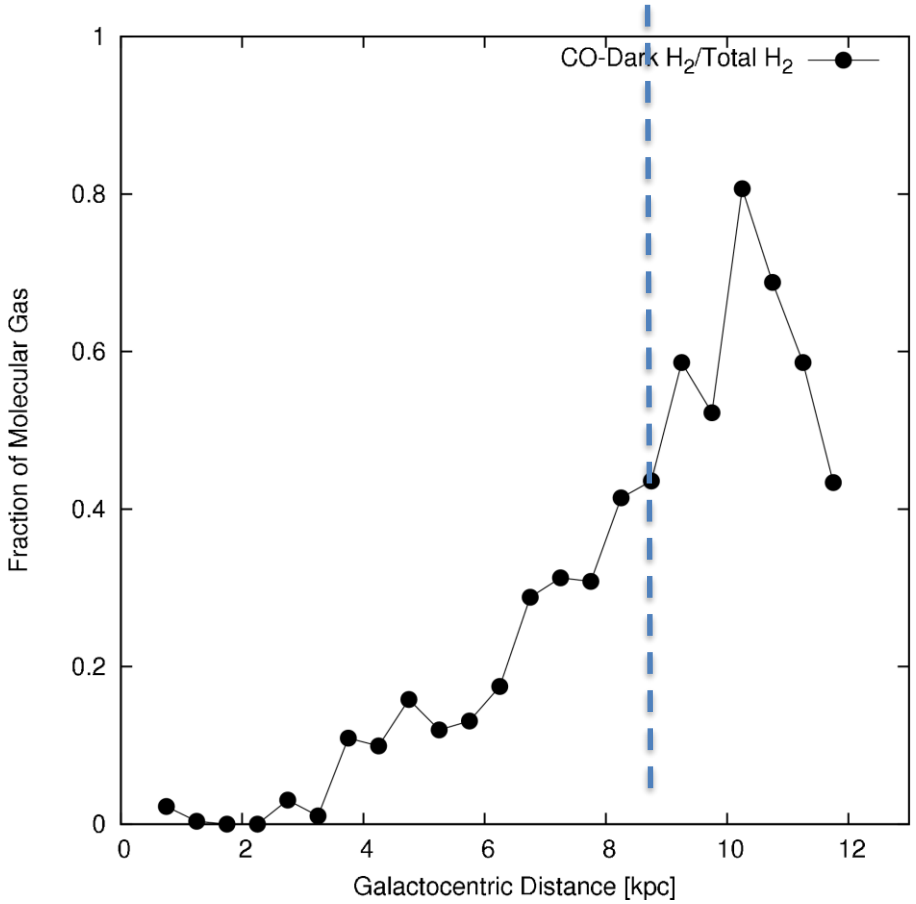

Traced by CO rotational lines

$N(H)+2N(H_2) > 5x10^{21}$ $cm^{-2}$

Traced by 21cm line

# CO Dark $H_2$

- The CO Dark $H_2$ gas adds ~30% to molecular mass of milky Way – the reservoir of material for future star formation
- The fraction of CO Dark $H_2$ gas increases dramatically with distance from the Galactic Center reaching 0.8 @ 11 kpc
- GUSTO will image CO Dark $H_2$ in individual clouds at different evolutionary stages in the Milky Way

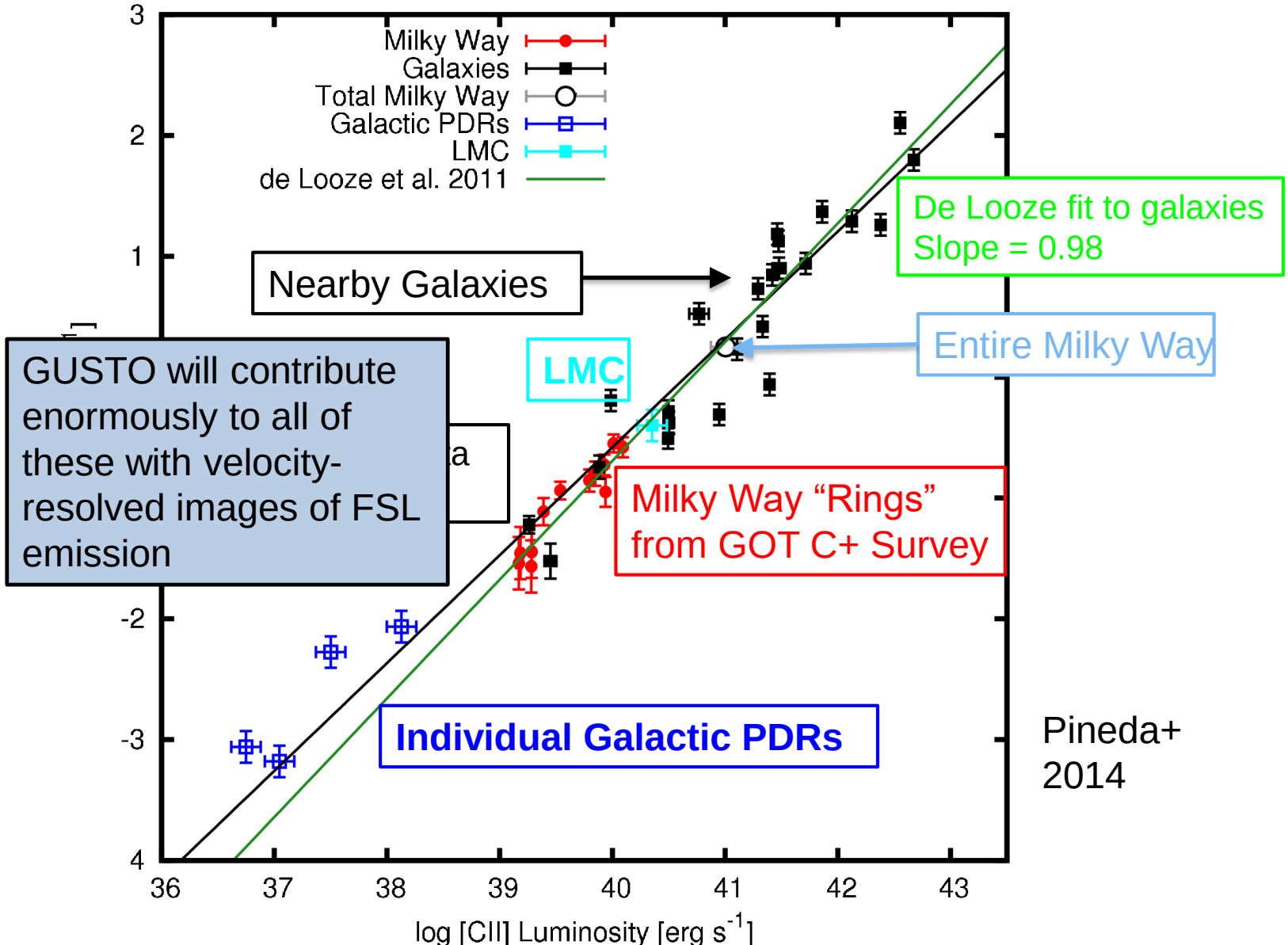



Pineda+ 2013

Is this a result of metallicity? If so, what are we missing in low-Z galaxies?

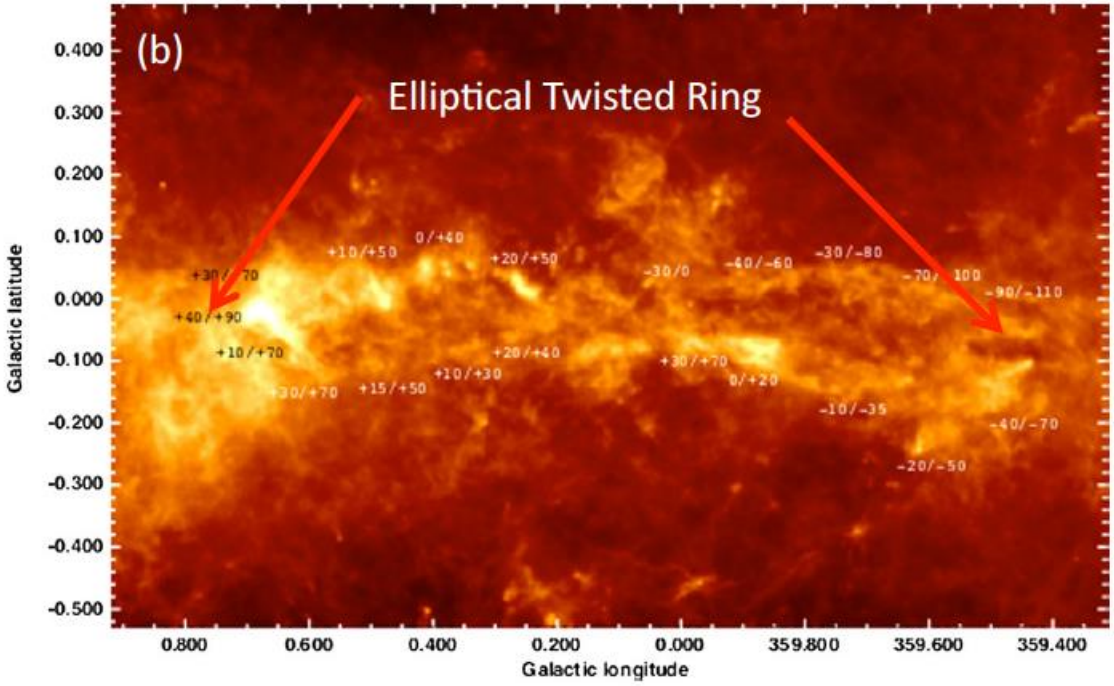
GUSTO will image clouds including CO Dark $H_2$ in the Large Magellanic Cloud

# [CII] as a Tracer of Star Formation



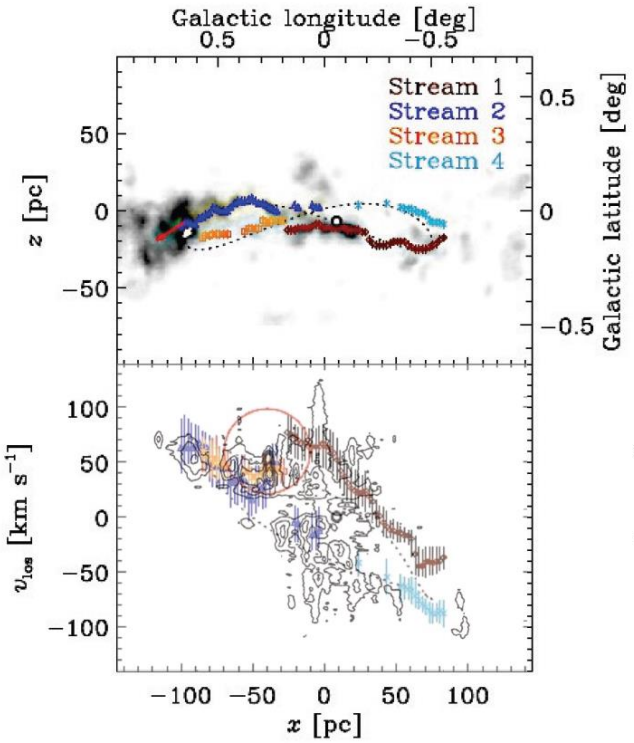

Pineda+ 2014

# GUSTO and the Galactic Center



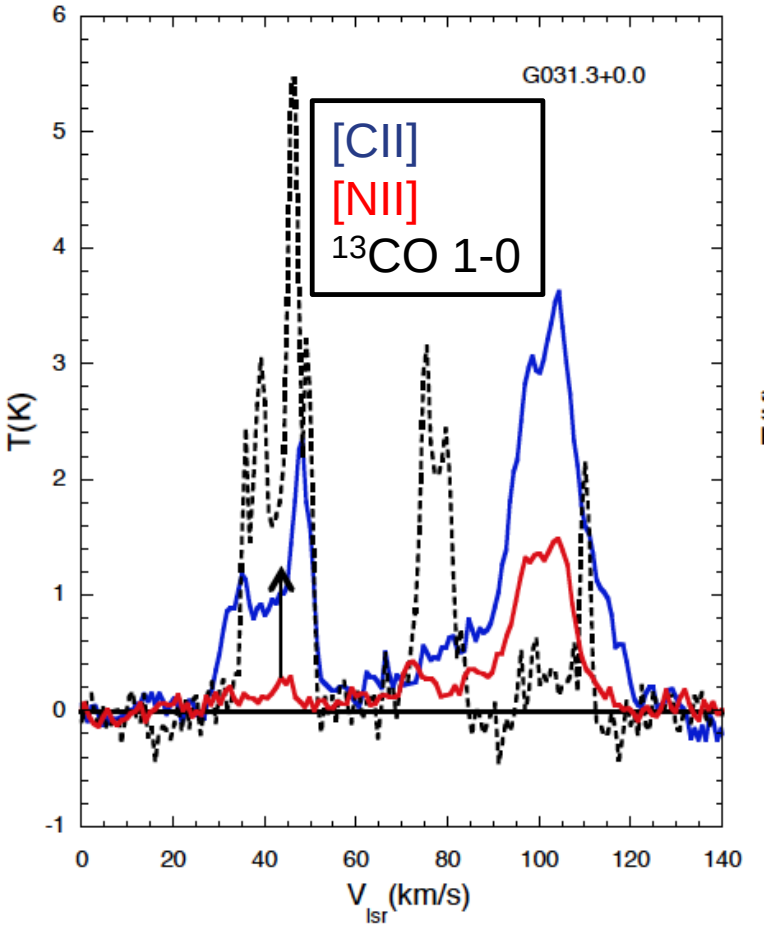

Relevant data to date: STRIP MAP in Galactic Longitude with Herschel HIFI

GUSTO will provide key observations to constrain models of mass flow into, around, and out of the Galactic Center.




Langer+ 2017

# Galactic Center Has Large Quantity of Ionized Gas Mixed with Neutral & Molecular Gas




All these tracers are required to unravel the complex kinematics and dynamics of the Galactic Center region
[CII] comes from ionized and neutral regions: [NII] from ionized gas only

[NII] is essential to separate contributions to the [CII] emission

GUSTO will image the entire Galactic Center region in [CII] and [NII] as part of the Galactic Plane Survey

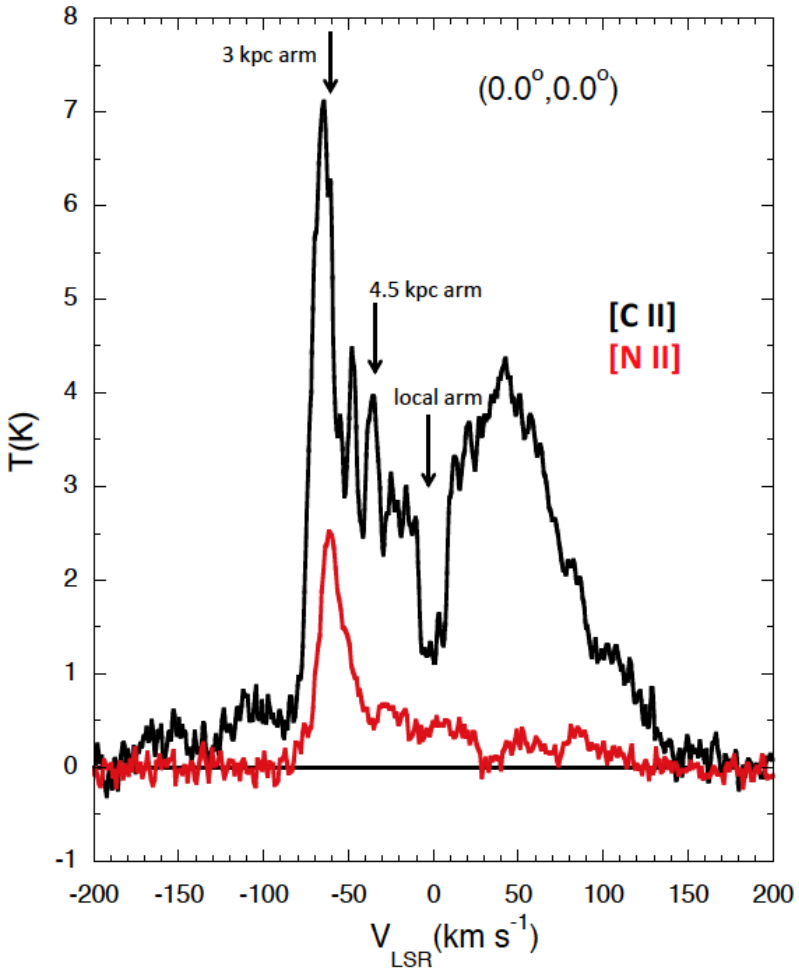
Langer, Goldsmith, & Pineda 2016

# GUSTO Observations

When you observe *towards* the Galactic Center you of course get much more than that.

This again emphasizes the need for high spectral resolution along with **velocity coverage of at least 350 km/s.**

A 2D (spatial)+ velocity image is required to unravel what is going on where.




[CII] & [NII] Towards G.C. Langer+ 2017

# GUSTO Surveys

| Survey Name | Survey Area | Angular Resolution | 3 sensitivity (erg/s/cm$^2$) |
|---|---|---|---|
| GPS | 121 deg$^2$ baseline<br>72 deg$^2$ threshold | 1.0' baseline<br>1.4' threshold | 8.8 x $10^{-6}$ [CII]<br>4.6 x $10^{-6}$ [NII]<br>8.6 x $10^{-5}$ [OI] |
| LMCS | 25 deg$^2$ baseline<br>6.5 deg$^2$ threshold | 1.0' baseline<br>1.0' threshold | 4.4 x $10^{-6}$ [CII]<br>2.3 x $10^{-6}$ [NII]<br>4.3 x $10^{-5}$ [OI] |
| TDS | 3.5 deg$^2$ baseline<br>0.8 deg$^2$ threshold | 1.0' baseline<br>1.4' threshold | 2.2 x $10^{-6}$ [CII]<br>1.1 x $10^{-6}$ [NII]<br>2.1 x $10^{-5}$ [OI] |

$-25^o < l < +28^o$

$|b| < 1.1^o$

# Summary

GUSTO will transform our understanding of Fine Structure Line Emission and will revolutionize the availability of velocity-resolved large-scale images for a wide variety of astronomy.

GUSTO will set the stage for higher angular resolution observations by upGreAT or other instruments on SOFIA and by the Origins Space Telescope or other very large aperture future facilities.

The technology driven by ground-based instruments, KAO instruments, Herschel HIFI, GREAT, upGREAT, STO, and STO2, makes the multi-pixel 3-band simultaneous observation concept of GUSTO mature at this time.

The science output will be exploited by the capable GUSTO science team, but will also be made available to the broader astronomical community through U of A, SAO, and NASA IRSA.